Two-layer interconnection network architectures based on integrated concentric orbital angular momentum emitters

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Abstract: Novel architectures for two-layer interconnection networks based on concentric OAM emitters are presented. A scalability analysis is done in terms of devices characteristics, power budget and OSNR by exploiting experimentally measured parameters.

OCIS codes: (130.3120) Integrated optics devices; (130.4815) Optical switching devices

1. Introduction

The scalability of the current electrical interconnection networks for data center connectivity is hampered by several challenging technological issues [1]. An effective solution to overcome these issues is represented by optical interconnection networks based on optical switching [2]. By exploiting simultaneously different multiplexing domains, further enhancing of the scalability and the total capacity can be obtained [3]. A two-layer orbital angular momentum (OAM) and wavelength based switch architecture has been presented in [4], based on a single and not tunable OAM emitter with multiple superimposed gratings. Here we present two novel architectures based on integrated concentric OAM emitters/modulators which can be independently tuned, thus making the interconnection network completely flexible over the two layers, i.e. OAM and wavelength domain. We analyzed the scalability of the architectures in terms of OAM emitter/multiplexer general characteristics and we performed a power budget and OSNR degradation analysis. The physical parameters exploited for the analysis are experimentally measured, in particular the OAM crosstalk-induced bit error rate (BER) degradation is measured at 30Gb/s.

2. Two-layer interconnection network architectures

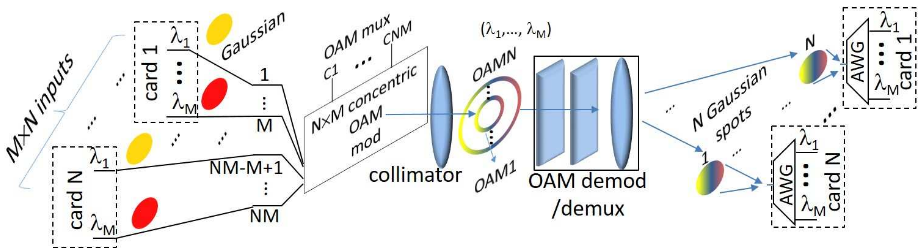


Fig. 1: Two-layer interconnection network architecture based on concentric OAM emitters/modulators (OAM mux).

Fig. 1 shows an architecture based on concentric OAM emitters/modulators. The switch has a total number of M×N optical inputs and M×N optical outputs. The ports are logically grouped in *N* subsets, corresponding to the number of cards of an Ethernet switch. Each set of ports represents the number of I/O ports of a card in an Ethernet switch architecture. The ports of the same subset are addressed by the wavelength domain, while the different sets of ports (i.e. cards) are addressed by the OAM domain. Each port of the OAM switch accepts a Gaussian signal, i.e. with the phase front having a Gaussian spatial distribution, at a wavelength within the allowed set of *M* wavelengths (λ1,...λM). For each input port, an OAM modulator converts the signal onto an OAM mode, i.e. with a phase front with an helical spatial distribution, of order *l* among a set of *N* OAM modes (OAM 1, …,OAM N) depending on the targeted output ports subset. The OAM modulator can be implemented with single integrated microrings with a superimposed grating, which emit the OAM beam in a direction orthogonal with respect to the microring plane [5]. The order of the converted signal is set with a control signal (Ci) by thermal tuning [6]. Since the N×M OAM emitters/modulators are concentric, the OAM signals with different OAM orders coming from different ports are spatially multiplexed. The multiplexed OAM beams are directed to an OAM demultiplexer/demodulator which spatially separates all the OAM modes of different orders and at the same time convert them to Gaussian modes, which can be propagated e.g. through a waveguide or an optical fiber. The OAM demodulator/demultiplexer can be implemented a passive device build with two polymetilmetacrylate (PMMA) free-space diffractive optical elements suitably patterned followed by a lens as demonstrated in [7], or with a commercial multiplane light converter [8]. All the M wavelengths are demultiplexed, i.e. spatially separated, by an arrayed waveguide (AWG) and directed to the corresponding output port. This scheme is very compact since the functionalities of modulation and multiplexing are implemented with a single integrated device. The number of OAM modulators that can be integrated on the same OAM mod/mux limits the number of input ports.

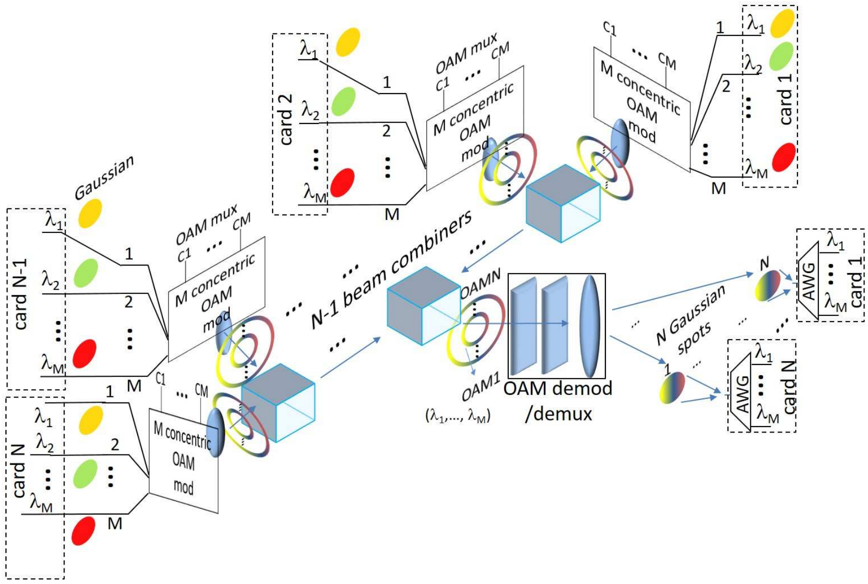


Fig. 2: Two-layer interconnection network architecture based on parallel OAM mux devices. Implementation with N parallel OAM mux with M concentric OAM emitter/mod per each OAM mux.

An alternative implementation, which allows to reduce the number of concentric OAM emitters/modulators that need to be integrated, is shown in Fig. 2. This alternative architecture is based on parallel concentric OAM emitters/modulators. All the M signals coming from each of the N cards (N×M total input signals) are coupled to an OAM modulator/multiplexer implemented with M concentric OAM emitters/modulators independently tunable. The emitted OAM signals are collimated and coupled with (N-1) free-space beam combiners and sent to the demodulation/demultiplexing part, which is equal to the one shown in Fig. 1.

3. Scalability analysis

In the architecture shown in Fig. 1, the total number of ports corresponds to the number of concentric OAM emitters/modulators that can be integrated on the same chip. This number is limited by the maximum allowed size (e.g. diameter) of each OAM emitter/modulator, which influences the OAM beam divergence-induced losses, and by the minimum allowed distance between two concentric emitters/modulators. The beam emitted by the concentric OAM emitters/modulators is collimated by a lens and, according to the ray optics laws, diverges depending on the diameter of the OAM emitter/modulator (D) and the collimator focal length (f). The OAM beam divergence should be limited in order to keep the beam spot size smaller than the aperture of the OAM demod/demux (T). For a fixed maximum allowed T, it becomes Dmax<T*f/L, where L is the distance between the collimator and the OAM demod/demux. Fig. 3 (a) shows Dmax vs. f and L for T=10mm, which represent a safe limit for standard optical devices. The closer the distance between the collimator and the OAM demod/demux, the higher the size allowed for the larger OAM emitters/modulators. Considering a collimator with high numerical aperture, e.g. NA=0.5, with f=10mm, for a distance L<200mm, Dmax >500µm. The maximum number of concentric emitters in the OAM mux is K=(Dmax-Dmin)/2S, where S is the minimum separation among two concentric OAM emitters and Dmin is the minimum diameter for the OAM emitter. Fig. 3 (b) shows total number of ports K=M×N vs Dmax and S, fixing Dmin to 80µm [6]. For S=6µm, Dmax=200µm is required to have 10 concentric OAM emitters. In order to have hundreds of ports, an S<2µm is required. Since the minimum allowed S depends on the particular technological constraints, the number of total ports can be alternatively improved by exploiting a parallel of OAM mux free-space coupled as shown in Fig. 2. The total number of ports (N×M) vs. the number of ports per OAM mux (K) and the number of parallel OAM mux, is shown in Fig. 4 (a). With K=8 OAM emitter/mod, 128 ports can be obtained with a parallel of 16 OAM mux. In order to investigate the limitation to the scalability due to the intrinsic architectures losses, a power budget and optical signal to noise (OSNR) analysis is carried out. Fig. 4 (b) shows the scheme of the optical device chain from the transmitting to the receiving card. The chain is composed by a laser (TL), a modulator (mod), the OAM mux, the free-space combiners, the OAM demux, an arrayed waveguide (AWG) and the photoreceiver (PR). The power budget analysis is carried out considering the following parameters: laser output power (13dBm), laser output OSNR (55dB), modulator loss (6dB), OAM emitter efficiency loss (7dB), OAM demux loss (3dB), AWG loss (2dB), photoreceiver sensitivity (-12dBm @BER 10^{-12}). The analysis shows that 4 parallel OAM mux ensures BER<10^{-12}. By inserting an EDFA (gain 20dB, saturation power 12dBm, noise figure 4.5dB) before the photoreceiver, the OSNR degradation due to the EDFA noise is also considered. The number of parallel OAM mux can be increased in this case up to 18. If a second EDFA is placed after the laser (gain 20dB, saturation power 20dBm), up to 26 OAM mux can be parallelized. The OAM crosstalk-induced penalty has been also included in the analysis. The crosstalk is measured in an experiment where 3 consecutive OAM modes are generated at the same wavelength (worst case) with three concentric OAM emitters. The measurements are performed on a 30Gb/s OOK signal. The BER is measured after the OAM demod/demux when only a single OAM channel is turned on and when all OAM channels are on. The crosstalk induced penalty is <1dB (see Fig. 4(c)), which do not significantly affects the power and OSNR budget analysis.

[mm]

L [mm] \ f	2	4	6	8	10
100	200	400	600	800	1000
200	100	200	300	400	500
300	66.6	133.3	200	266.6	333.3
400	50	100	150	200	250

(a)

[mm]

S [µm] \ Dmax	100	200	400	600	800	1000
2	5	30	80	130	180	230
4	2	15	40	65	90	115
6	1	10	26	43	60	76
8	1	7	20	32	45	57
10	1	6	16	26	36	46

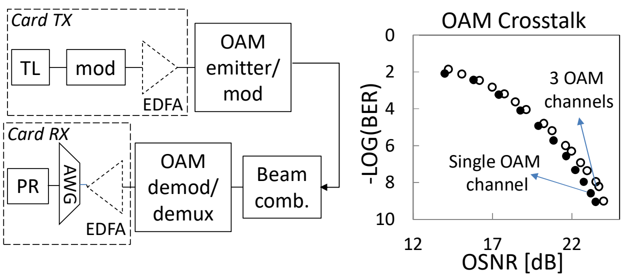
(b)

Fig. 3: (a) Maximum OAM emitter diameter (Dmax) vs. collimator focal length (f) and distance between collimator and OAM demux (L). (b) Total number of ports (NM) vs. Maximum OAM emitter diameter (Dmax) and separation between adjacent OAM emitters (S).

Number of parallel OAM mux

Number OAM emitter/mod(K)	2	4	8	12	16	20
4	8	16	32	48	64	80
8	16	32	64	96	128	160
12	24	48	96	144	192	240
16	32	64	128	192	256	320
20	40	80	160	240	320	400
40	80	160	320	480	640	800
60	120	240	480	720	960	1200

(a)



(b) (c)

Fig. 4: (a) Total number of ports (NM) vs. the number of ports per OAM mux (K) and the number of parallel OAM mux. (b) Optical device chain from the transmitting to the receiving card. (c) BER vs OSNR for OAM crosstalk evaluation.

4. Conclusions

Novel two-layer interconnection networks architectures exploiting OAM and wavelength as switching domains and based on concentric OAM emitter/modulators are presented. The scalability of the architectures is analyzed in terms of OAM emitter/multiplexer general characteristics and performing a power budget and OSNR degradation analysis through the optical device chain. BER measurements at 30Gb/s performed to evaluate OAM crosstalk-induced degradation indicate that the introduced penalty is <1dB and do not affect the scalability of the interconnection network.

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